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Offline calibrations and performance of the CMS pixel detector

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Abstract

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The CMS pixel detector, divided into barrel and endcap subdetectors, has 66 million pixels. We present the offline algorithms and results for the gain/pedestal and Lorentz angle calibrations. The determination of the optimal clock delay settings with initial data is described. The expected detector performance from Monte Carlo simulations is compared to the real performance in 7 TeV proton-proton collisions.

Keywords: Pixel detectors, calibrations, CMS experiment, LHC detectors

1. Introduction

The pixel detector of the CMS experiment [1] at the Large Hadron Collider (LHC) has three layers in the barrel (BPIX) and two disks at the forward and backward end (FPIX). The BPIX layers are 53 cm long and at an average radius¹ of $r = 4.4, 7.3$, and 10.2 cm. Each layer is composed of modules containing 8 or 16 readout chips (ROC) [2] and a $285\mu\text{m}$ thick sensor [3]. Within each layer, the modules are arranged such that there is some overlap in $r\phi$. The FPIX disks are located at $z = \pm 35.5$ cm and $z = \pm 48.5$ cm, covering the radial interval $6 < r < 15$ cm. To achieve optimal coverage, the FPIX modules contain 2, 5, 6, 8, or 10 ROCs with a $270\mu\text{m}$ thick sensor [4]. In the entire detector the pixel size is $100 \times 150\mu\text{m}^2$. In the BPIX the short pixel side is in the $r\phi$ direction, while it is in the radial direction for the FPIX². Each ROC has 52×80 pixels, arranged for readout purposes in double columns with 160 pixels. The BPIX contains 48 million pixels and the FPIX has

18 million pixels. The pixel detector provides three hits for charged particle track reconstruction in the region $|\eta| < 2.2$ and two hits for $2.2 < |\eta| < 2.5$.

The CMS pixel detector is immersed in a 3.8 T solenoidal magnetic field, which leads to a significant Lorentz drift of the charge carriers in the sensor. This implies substantial charge sharing between adjacent pixels in the $r\phi$ direction in the BPIX and to a lesser extent also in the FPIX. Low pixel thresholds in combination with the analog signal readout allow for a much improved position resolution compared to the binary expectation ($\text{pitch}/\sqrt{12}$). The small pixel size along (global) z ensures a high resolution in the longitudinal direction.

Because of charge sharing among pixels, the total deposited charge is usually spread over several pixels. In the reconstruction algorithm, adjacent pixels are combined into clusters. The cluster position is determined in a two-step procedure: First, a fast algorithm computes the hit position from the x and y cluster projections. In a second step, pre-computed cluster shapes (templates) from the PIXELAV simulation [5] are used that include modeling of radiation damage [6]. The templates require the knowledge of the track incidence angle and therefore cannot be used in a first-pass reconstruction. For unirradiated sensors, the templates improve the position resolution for large-charge clusters, especially the resolution in the (local) x direction for $|\eta| > 1.5$. For irradiated sensors, the template reconstruction provides substantial position resolution improvements for all clusters.

¹The CMS experiment uses a right-handed coordinate system, with the origin at the nominal proton-proton collision point, the x axis pointing towards the center of the LHC ring, the y axis pointing upwards (perpendicular to the LHC plane), and the z axis pointing along the anticlockwise beam-direction. The polar angle (θ) is measured from the positive z axis and the azimuthal angle (ϕ) is measured from the positive x axis in the xy plane. The radius (r) denotes the distance from the z -axis and the pseudorapidity is defined by $\eta = -\ln \tan(\theta/2)$.

²The local coordinate system on the modules has the x axis along the short pixel side, the y axis along the long pixel side, and the z axis parallel to the $\vec{E}$ field in the sensor. The local angle α (β) is measured with respect to the x (y) axis. In the following, local coordinates will be used (exceptions will be mentioned explicitly).

2. Calibrations

The offline pixel detector calibrations comprise procedures or post-calibration analyses that are too CPU intensive to be done in real time with the detector (see Ref. [7] for a discussion of the online calibrations). Here we discuss the calibration of the readout signal to charge, the Lorentz angle, and the delay setting analysis.

2.1. ADC to Charge

The charge signal from the sensor pixel enters a two-stage charge-sensitive amplifier/shaper system in the pixel unit cell (PUC). Pixels with a signal above an ‘absolute’ threshold will copy their signal to data buffers in the ROC periphery. If the charge is above the ‘in-time’ threshold, they will be associated to the correct LHC bunch crossing and they will be read out if confirmed by the first level trigger.³ The analog charge signal is digitized in an analog-to-digital (ADC) converter located in the electronics room [8].

The ADC-to-charge calibration proceeds in two steps. First, in a dedicated standalone calibration run (3–6 hour duration, depending on the setup) of the pixel detector, all pixels are subject to charge injection from around 4000 electrons into the saturation regime (> 50000 electrons). Charge is injected into a small fraction of all pixels on a ROC to minimize the effects of crosstalk. The pattern of injected pixels is varied such that the entire ROC is covered. The charge injection is controlled by a digital-to-analog-converter called VCAL. The relation between VCAL and injected charge Q in electrons, $Q = 65.5 \times \text{VCAL} - 414$, has been obtained from dedicated x-ray source calibrations with variable x-ray energies (17.44 keV from Mo, 22.10 keV from Ag, and 32.06 keV from Ba, excited from a primary Am source). About 90% of the barrel pixel modules have been calibrated with two lines (Mo, Ag), while 10% have undergone more extensive calibration tests with three lines. The observed variation of the injected charge amounts to 13.6% (8.2%) for ROCs measured with 2(3) lines. It is planned to improve the calibration of the injected charge with the deposited charge of minimum ionizing particles as a function of path length in the sensor.

Figure 1 shows a typical example for the pixel response with a slight non-linearity for small charges and the saturation at large charges (the energy deposition of a minimum ionizing particle corresponds to roughly 22000 electrons). The non-linearity at low charges can

Figure 1: Example ADC response as a function of injected charge in VCAL units (see text for conversion to electrons). The red line is a first degree polynomial fit to the data in a restricted VCAL range.

be reduced at the cost of higher power consumption by the ROC.

Figure 2: Distributions of the gain and pedestal constants for each pixel as obtained in a dedicated calibration run in October 2009.

In the second step of the ADC-to-charge calibration, a polynomial of first degree is fit to the ADC vs charge measurements. The fit is performed in a restricted VCAL range to minimize the influence of the non-linearities at high charge. The resulting two parameters (gain and pedestal) are displayed in Fig. 2 as obtained in a calibration run from October 2009. The gain is the inverse slope and the pedestal is the offset in Fig. 1. The parameters are very stable and are determined about every four months for control purposes. The small fraction of negative pedestals does not affect the performance of the pixel detector as the corresponding pixel charge would be below threshold. The large number of calibration constants requires a compression for use in the high-level trigger (HLT) and in the recon-

³See Ref. [7] for a discussion of absolute vs. in-time thresholds.

struction software. For the HLT, both gain and pedestal are averaged per column. In the reconstruction, the gain is averaged per column and the pedestal is stored for each pixel.

2.2. Lorentz Angle

The charge carriers in the sensor are influenced by the applied electric field and the magnetic field. The resulting deflection by the Lorentz angle θ_{LA} depends on the bias voltage, magnetic field strength, temperature, and irradiation. In the BPIX, the Lorentz deflection leads to significant cluster widening along the x direction and charge sharing among pixels. The average shift of the hit position is $53\text{ }\mu\text{m}$ ($10\text{ }\mu\text{m}$) in the BPIX (FPIX) and needs to be corrected in the hit reconstruction algorithms. Two methods are employed for the Lorentz angle determination.

The minimum cluster size method relies on the fact that the cluster size along x depends on the particle's incidence angle and has a minimum for tracks (anti)parallel to the drift direction of the charge carriers. The Lorentz angle is measured by determining the minimum of the cluster x size vs. the cotangent of the angle α . This method is applicable for tracks that have relatively large incidence angles, such as cosmic ray muons [9] or small transverse momentum ($p_{\perp}$) tracks in proton-proton collision events. For the latter analysis, tracks with $p_{\perp} > 100\text{ MeV}$ and a track fit $\chi^2/\text{dof} < 2$ are selected. Clusters are required to have a cluster y size of $N_y > 1$ to avoid single pixel clusters. Clusters with edge pixels are excluded from the analysis.

In the grazing angle method [10] the charged particle trajectory is extrapolated through the sensor. This allows the determination of the electron drift distance in the x direction vs. the production depth in z . Tracks selected from a high-purity sample are required to have $p_{\perp} > 3\text{ GeV}$ and $\chi^2/\text{dof} < 2$. Well measured clusters with size $N_y > 3$ and total charge < 120000 electrons are required to have a track residual of $< 50\text{ }\mu\text{m}$. As in the first method, clusters containing edge pixels are excluded from the analysis. The observed linear relation is fit with a first degree polynomial.

The results of the two methods agree well for data from cosmic ray muons ($\tan \theta_{LA} = 0.405 \pm 0.003$) and from proton-proton collisions (minimum cluster method: $\tan \theta_{LA} = 0.409 \pm 0.002$ and grazing angle method: $\tan \theta_{LA} = 0.391 \pm 0.010$). The quoted errors are statistical only. The estimated largest systematic uncertainties of the order 3% in both methods originate from the choice of the fit range. Cross checks of the methods, when the magnetic field was at 0 and 2 T, provide results consistent with the expectation within the

statistical uncertainty. These results may be compared to the PIXELAV simulation [5], which agrees well for a Hall factor of 1.02.

2.3. Delay Scan

The pixel detector system clock needs to be set with a well-defined optimal phase with respect to the LHC beam crossings. In a dedicated delay calibration run, the delay settings are changed in 2 ns steps and data is collected for a few minutes per delay point.

Figure 3: Hit efficiency (red symbols) and cluster size (black symbols) vs. global delay setting. The ordinate on the right side provides the scale for the efficiency, the ordinate on the left side is for the cluster size. The hit efficiency and cluster size are averaged over the entire detector.

The goal is to optimize the cluster efficiency (relevant for the tracking efficiency), resolution (for tracking and vertexing fits) and charge measurement (for possible specific ionization energy loss measurements). Two observables are currently used for this: the cluster size and the cluster efficiency. The cluster size depends on the delay setting as a wrong setting will remove the small-charge digis. Because of time-walk they will be associated with a bunch crossing after the nominal one and will be lost.

The efficiency is determined as the ratio of the number of found hits divided by the number of expected hits. The latter are found by extrapolating the trajectory to individual pixel modules and searching for a corresponding hit within 0.05 cm (0.2 cm) along x (y) of the impact point. The hit efficiency is determined in events where one primary vertex at the nominal position with at least four tracks is reconstructed. All tracks are used with $p_{\perp} > 0.9\text{ GeV}$, more than 10 silicon strip hits, and consistent with originating from the primary vertex. Hits at module edges are excluded from the analysis. The track is required to have hits on pixel layers different from

the one under study. Figure 3 illustrates an efficiency plateau at $\varepsilon > 99\%$ with a width of about 12 ns.

For the determination of the cluster size, clusters with a total charge of $Q > 12000$ electrons were selected. The cluster charge was not corrected for the trajectory path length in the sensor to reduce the dependence on the tracking. The cluster size shows an asymmetrical behavior with a maximum for a delay setting of 10 ns. This is chosen as the operational setting for the pixel detector, where the cluster size promises the best resolution while being safely on the efficiency plateau.

The delay scan calibration runs were performed in 2009 with enough statistics for one global delay setting for the entire detector. In 2010, longer calibration runs were performed that allowed the determination of delay settings for each readout group. The largest corrections to the a-priori determined settings, calculated from cable propagation delays, amounted to 3 ns (8 ns) in the BPIX (FPIX).

3. Performance

The performance of the pixel detector is quantified with studies of the hit efficiency, pixel thresholds, the agreement of data and Monte Carlo (MC) simulation for cluster variables, and the hit resolution.

3.1. Hit Efficiency

The hit efficiency is determined as described in section 2.3. Known defective modules are excluded from this analysis. In the real detector, the measured hit efficiency is larger than 99% in all BPIX layers and FPIX disks, except for the first BPIX layer, where it is at 98%. The hit efficiency in the MC simulation is consistent with the efficiency measured in data in every BPIX layer and FPIX disk. Based on studies in MC simulated event samples, the low efficiency in layer 1 is attributed to tracks from secondary particles (produced for instance through hadronic interactions in the first BPIX layer) which do not leave a reconstructable hit in the first layer.

3.2. Thresholds

In the absence of a more precise VCAL calibration (cf. section 2.1), a comparison of the cluster size in data and MC simulation provides the best estimate of the in-time pixel thresholds (in electrons). The PIXELAV simulation of the x (y) cluster size vs. the angles $\cot\alpha$ ($\cot\beta$) is compared against the data in Fig. 4

The best agreement between data and simulation is obtained for an in-time threshold of 3200 electrons. This result is based on a single threshold for all pixels

Figure 4: Cluster size vs. local track incidence angle in data and the PIXELAV simulation for the (top) x direction and (bottom) y direction.

and the specific response model implemented in PIXELAV. Figure 4 indicates a small systematic excess of the y cluster size in the MC simulation. It is not possible to describe simultaneously the x and y size dependence satisfactorily with one single threshold. The pixel threshold might be different for pixels that are part of clusters contained within a double column than for clusters covering more than one double column. Further studies are investigating this hypothesis.

3.3. Cluster Distributions

The cluster charge distributions in data and MC simulation are compared in Fig. 5. The cluster charge is scaled to correspond to normal track incidence. The MC simulation, normalized to the same number of entries as the data, describes the data quite well. In the BPIX distribution, there is a small shift and a somewhat

Figure 5: Cluster charge in the BPIX (top) and FPIX (bottom), corrected for sensor path length. The insets show the same distributions in a logarithmic y scale.

underestimated width of the main peak in the MC simulation. In the FPIX, the MC simulation overestimates the peak width slightly. The tails of the distribution are well described, as evident from the insets.

In the MC simulation, pixel thresholds of 2733 (2483) electrons are used for the BPIX (FPIX); the production of this MC simulated event sample predates the threshold study of section 3.2.

3.4. Hit Resolution

The intrinsic hit resolution σ_{hit} is measured with tracks passing through overlapping modules in a single layer of the BPIX. The expected hit position in the x or y direction is determined on both modules from track extrapolation, without including the layer under study

for an unbiased estimate. The (double) difference $\mathcal{D}$ of the expected position difference Δ_{pred} and the measured position difference Δ_{meas} is determined and fit to a Gaussian distribution. The difference of the estimated positions is about an order of magnitude more precise than the individual expected positions. From the width of the double difference, the intrinsic resolution is determined as $\sigma_{\text{hit}}^2 = [\sigma(\mathcal{D})^2 - \sigma(\Delta_{\text{pred}})^2] / \sqrt{2}$, where $\sigma(\Delta_{\text{pred}})$ is computed for each overlap site as the mean of the error distribution from the trajectory extrapolation. The factor $\sqrt{2}$ corrects for the contributions from the residuals in both overlap sites and is based on the assumption that the resolution is identical for both (this is true only if the clusters have similar charge distributions). The advantage of this method is a strongly reduced dependence on extrapolation and misalignment uncertainties.

The measurement is performed using overlap sites with more than 20 tracks with $p > 2.5$ GeV (to limit the effects of multiple scattering), a fit probability of $P(\chi^2) > 10^{-3}$, and more than 5 hits. We require a track extrapolation error of less than $25 \mu\text{m}$ and reject clusters at module edges.

The resulting hit resolution in the x direction is $\sigma_{\text{hit}} = (12.7 \pm 2.3) \mu\text{m}$ [$\sigma_{\text{hit}} = (14.1 \pm 0.5) \mu\text{m}$] in data [PIXELAV simulation] and in the y direction we find $\sigma_{\text{hit}} = (28.1 \pm 1.9) \mu\text{m}$ [$\sigma_{\text{hit}} = (24.1 \pm 0.5) \mu\text{m}$] for data [PIXELAV simulation]. The charge sharing, due to the Lorentz drift, leads to a x resolution that is more than a factor two better compared to $\text{pitch} / \sqrt{12}$. The detector performance is consistent with the expectation in the PIXELAV simulation. Given the chosen pixel sizes, the current value of the Lorentz angle provides the optimal x resolution. With accumulating radiation damage, the necessary increase of the bias voltage (currently 150 V in the BPIX and 300 V in the FPIX) will result in a smaller Lorentz angle and somewhat degraded resolution.

4. Conclusions

The CMS pixel detector is performing according to design specifications. The offline calibrations discussed in this presentation are an essential contribution in reaching this state.

The detector is operated at low absolute pixel thresholds of around 2500 electrons, corresponding to in-time thresholds of around 3200 electrons. The gain and pedestal calibration equalizes the response of the 66 million pixels. Two methods for the Lorentz angle calibration provide consistent results in agreement with the expectation from the PIXELAV simulation.

The hit resolution studies confirm the expected benefits of the analog signal readout. The charge sharing among neighboring pixels allows for a precise interpolation of the hit position and provides a hit resolution of $\sigma_{\text{hit}} = (12.7 \pm 2.3) \mu\text{m}$ in the azimuthal direction, in excellent agreement with the expectation from the detailed detector simulation.

References

- [1] R. Adolphi *et al.* [CMS Collaboration], “The CMS experiment at the CERN LHC,” JINST **3**, S08004 (2008).
- [2] H. C. Kastli, *et al.*, “Design and performance of the CMS pixel detector readout chip,” Nucl. Instrum. Meth. A **565**, 188 (2006).
- [3] Y. Allkofer *et al.*, “Design and performance of the silicon sensors for the CMS barrel pixel detector,” Nucl. Instrum. Meth. A **584**, 25 (2008).
- [4] G. Bolla *et al.*, “Design and test of pixel sensors for the CMS experiment,” Nucl. Instrum. Meth. A **461**, 182 (2001).
- [5] M. Swartz *et al.*, “Observation, modeling, and temperature dependence of doubly peaked electric fields in irradiated silicon pixel sensors,” Nucl. Instrum. Meth. A **565**, 212 (2006).
- [6] M. Swartz, *et al.*, “A new technique for the reconstruction, validation, and simulation of hits in the CMS pixel detector,” PoS VERTEX2007, 035 (2007).
- [7] B. Kreis, these proceedings.
- [8] D. Kotlinski *et al.*, “The control and readout systems of the CMS pixel barrel detector,” Nucl. Instrum. Meth. A **565**, 73 (2006).
- [9] S. Chatrchyan *et al.* [CMS Collaboration], “Commissioning and Performance of the CMS Pixel Tracker with Cosmic Ray Muons,” JINST **5**, T03007 (2010).
- [10] B. Henrich and R. Kaufmann, Nucl. Instrum. Meth. A **477**, 304 (2002).